NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS TECHNICAL PREPRINT 3-63

BREAKUP OF VARIOUS LIQUID JETS BY SHOCK WAVES

By G. Morrell and Frederick P. Povinelli

(NASA LEWIS Tech. Preprint 3-63)

index NASA-LEWIS-TP-3-63

For Presentation at the 5th ~~Fifth~~ Liquid Propulsion
Symp. ~~osium~~ of the Chem. ~~ical~~ Propulsion
Inform. ~~ation~~ Agency,

Tampa, Fla. ~~Florida~~. Nov. ~~November~~ 12-14, 1963

BREAKUP OF VARIOUS LIQUID JETS BY SHOCK WAVES

By G. Morrell* and Frederick P. Povinelli**

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

16070

Breakup times of liquid jets in cross flow were measured in a shock tube. Three jet diameters (0.052, 0.0785, and 0.157 in.) of the liquids water, heptane, liquid oxygen, and three glycerol-water mixtures were studied. Breakup time decreased monotonically with an increase in gas velocity.

E-2312

A model based on mass removal from a liquid boundary layer gives fair agreement with the experimental data and permits quantitative estimates of breakup time or average mass removal rate.

With the assumption that atomization is the rate controlling process, it is shown how similarity parameters of three combustion instability theories may be evaluated in terms of engine design variables.

AUTHOR

INTRODUCTION

The process of breakup and atomization, produced by shock waves acting on liquid jets or drops, may be important in oscillatory combustion (1) either as an initiating or a driving mechanism. Information on the rate of this process should be helpful whether the oscillation is treated as a perturbation on the mean vaporization rate or as a heterogeneous detonation.

Although the literature on atomization is voluminous, the effects produced by shock waves have not been treated extensively. The primary interest has been in the threshold conditions for shattering. In several references (2,3,4) breakup times can be inferred from the pictorial sequences presented. Previous studies (5,6) of the breakup of water jets in shock tubes indicated that mass is removed by formation of a liquid boundary layer for flow conditions which are not too close to the threshold for breakup.

The purpose of this study was to test the predicted effects of liquid properties on breakup time. The breakup times for heptane, glycerine water, and liquid oxygen jets were obtained in the same apparatus used for the water studies. The results are analyzed in terms of the boundary layer model, and the possible significance of jet breakup in oscillatory combustion is also discussed.

---

*Chief, Chemical Rocket Fundamentals Branch.
**Student trainee.

APPARATUS AND PROCEDURE

A schematic diagram of the apparatus is shown in figure 1. Except for the oxygen flow system, no changes were made from the system described in reference 6. The square test section has an internal dimension of 2.721 inches to provide a cross-sectional area about equal to that of the 3-inch-diameter schedule 40 pipe used for the remainder of the shock tube. The liquid jet is injected vertically at a station approximately 51.5 inches from the diaphragm (16.7 diam) and flows out through a 1.25-inch-diameter opening in the floor of the test section. The length of the high-pressure section was 8 feet, which provided an action time of approximately 15 milliseconds. Action time is the time required for the pressure to decrease to one third of its initial value.

Wave speed was measured by two barium-titanate blast gages located 2 feet apart, and pressure behind the wave was monitored by a strain tube pressure transducer with a natural frequency of about 25 kilocycles and a range of 200 pounds per square inch. A sine-wave generator was used to provide a 2 kilocycle frequency for the time base. These four signals were displayed by a two-beam oscilloscope equipped with 100 kilocycle chopping amplifiers to produce four displays on a time sharing basis.

Back-lighted streak photographs were taken with a 35-millimeter shutterless high-speed camera at a film velocity of approximately 990 inches per second. The test section window facing the camera was masked, except for an axial slit 0.1 inch wide and 14 inches long. The oscilloscope, operated in the unswept mode, was photographed simultaneously by means of a mirror arrangement to provide a real time correlation with the picture of the breakup process. A 50 millimeter f/2 lens was used with a demagnification of 11. A typical streak photograph is shown in figure 2. For reference, a corresponding framing photograph is also shown.

The initial pressure in the test section was one atmosphere, and four values of initial pressure ratio (across the diaphragm) were used. These values together with the diaphragm materials are shown in the following table.

TABLE I. EXPERIMENTAL SHOCK TUBE CONDITIONS

Initial pressure ratio	Nominal shock Mach number (70° F)	Diaphragm material	Diaphragm thickness
1.68	1.115	Oiled onion-skin paper	2 sheets
2.63	1.225	Soft brass	0.0015 in.
7.12	1.506	Soft brass	0.004 in.
14.61	1.725	Spring brass	.007 in.

Gas velocity and density behind the shock wave were calculated from the measured value of shock velocity using the one-dimensional wave equations (7) at a temperature of 70° F. Laboratory temperature was 70°±5° F. Initial air density was taken as 0.07488 pound per cubic foot, and air viscosity was assumed to be constant at 1.205×10^{-5} pound per foot-second.

Three jet diameters, 0.052, 0.0785, and 0.157 inch, were used with each of the liquids water, heptane, oxygen, and three glycerol-water mixtures. With the exception of oxygen, all liquids were used at 70° F. The oxygen was passed through a liquid-nitrogen heat exchanger and then through a vacuum-jacketed line to the injector. Properties of the liquids used for computation of breakup time are given in the following table.

TABLE II. PHYSICAL PROPERTIES OF LIQUIDS

Liquid	Surface tension, lb/sec^2	Density, lb/ft^3	Viscosity, lb/(ft)(sec)
Water	0.161	62.4	6.72×10^{-4}
Heptane	.045	42.6	2.745×10^{-4}
Oxygen	.029	71.2	1.27×10^{-4}
15% Glycerol (by wt.)	.160	64.5	8.94×10^{-4}
58% Glycerol	.151	71.4	4.18×10^{-3}
79% Glycerol	.147	75.0	2.70×10^{-2}

The oxygen properties were taken for a temperature midway between the normal boiling points of oxygen and nitrogen.

RESULTS AND DISCUSSION

Examples of the dependence of breakup time on gas velocity are shown in figure 3. Breakup time is defined as the interval between passage of the shock front and the time when no further change in ligament structure is observed. The lines drawn through the points are based on visual fits and were not used for computational purposes. It is apparent, however, that the slope varies with the nature of the fluid and with the initial size of the jet. In some cases, the scatter is appreciable and cannot be attributed entirely to the uncertainty of assessing the termination point of the breakup process from the photographs. We have no explanation at this time for these occurrences. The data do indicate the expected monotonic decrease in breakup time with an increase in velocity, and there is no indication of a lower limit for the breakup time.

In a previous report (6) it was shown that a model based on the formation of a liquid sheet with mass removal from the boundary layers on both sides gave reasonable agreement with the observed data for water. The volumetric removal rate may be written

$$-\frac{dV}{dt} = (2\delta_l u_{l,av})\Big|_{x=L} \tag{1}$$

where δ_l and $u_{l,av}$ are both functions of x. (All symbols are defined in symbol list.) Assuming constant L and free-stream velocity, equation (1) may be integrated (6) to yield

$$t_b = 0.54\left(\frac{\rho_l}{\rho}\right)^{2/3}\left(\frac{\mu}{\mu_l}\right)^{1/3}\frac{R_o}{u}\sqrt{\frac{Re_o}{L/2R_o}} \tag{2}$$

The apparent length of the liquid sheet observed in these experiments could not be related to a simple function of Weber number and Reynolds number as was done previously for water. A dimensional analysis and least squares fit of the data yielded the following expression:

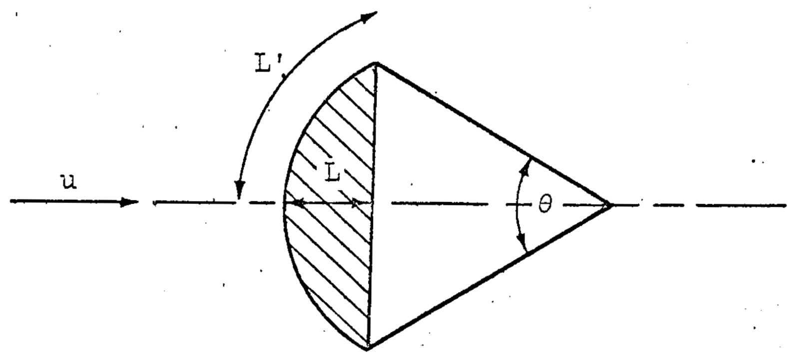
$$\frac{L}{2R_o} = 1 + 8.23\times10^{-3}\,(Re_o)^{0.418}(We_o)^{0.340}\left(\frac{\mu}{\mu_l}\cdot\frac{\rho_l}{\rho}\right)^{0.143} \tag{3}$$

Figure 4 shows a plot of the measured sheet length versus the calculated value from equation (3).

Substitution of equation (3) in equation (2) yields

$$t_b = 0.54\left(\frac{\rho_l}{\rho}\right)^{2/3}\left(\frac{\mu}{\mu_l}\right)^{1/3}\frac{R_o}{u}\sqrt{\frac{Re_o}{1 + 8.23\times10^{-3}(Re_o)^{0.418}(We_o)^{0.340}\left(\frac{\nu}{\nu_l}\right)^{0.143}}} \tag{4}$$

In recent experiments at our laboratory, however, Clark has shown that the assumption of a flat sheet of liquid is untenable. Two-dimensional photographs indicate that the liquid jet in cross flow tends to deform so as to approximate a segment of a larger cylinder. Assuming the cross section approximates a circular segment, as shown in the following sketch, a corrected surface length can be obtained from the apparent length.



For $\theta = 120^o$, which corresponds to the position where the dynamic pressure becomes zero, the corrected length, L', is given by $L' = 2.09\,L$, and substitution in equation (4) yields

$$t_b = 0.37\left(\frac{\rho_l}{\rho}\right)^{2/3}\left(\frac{\mu}{\mu_l}\right)^{1/3}\frac{R_o}{u}\sqrt{\frac{Re_o}{1 + 8.23\times10^{-3}(Re_o)^{0.418}(We_o)^{0.340}\left(\frac{\nu}{\nu_l}\right)^{0.143}}} \tag{5}$$

In figure 5 the measured values of the breakup time, t_b, are plotted against the values computed from equation (5). The agreement is far from perfect.

The calculated values tend to be high for long breakup times and somewhat low for low breakup times, especially for the most viscous liquids. The calculated times for liquid oxygen were all high, which may be due to cavitation of the jet or rapid vaporization of the deforming mass.

In spite of obvious shortcomings, the model does appear to give a reasonable prediction of breakup time as a function of experimental variables and may be used to predict conversion times in several combustion instability models. Also, substitution in equation (1) of the expressions for δ_l and $u_{l,av}$ of reference 6 yields the following expression for the average rate of mass removal per unit length of liquid jet:

$$-\frac{dM}{dt} = 8.47\left(\frac{\rho}{\rho_l}\right)^{1/3}\left(\frac{\nu}{\nu_l}\right)^{1/6}\sqrt{\rho_l^2 R_o u \nu_l} \times \sqrt{1 + 8.23\times10^{-3}(Re_o)^{0.418}(We_o)^{0.340}\left(\frac{\nu}{\nu_l}\right)^{0.143}}$$

For the case where $8.23\times10^{-3}(Re_o)^{0.418}(We_o)^{0.340}\left(\frac{\nu}{\nu_l}\right)^{0.143} \gg 1$, equation (5) gives the following dependence of t_b on the individual experimental parameters:

$$t_b \propto \left(\frac{R_o^{1.12}}{u^{1.05}}\right)\left(\frac{\rho_l^{0.6}}{\rho^{0.48}}\right)\left(\frac{\mu^{-0.03}}{\mu_l^{0.26}}\right)\sigma^{0.17} \qquad (6)$$

This expression may be compared with results obtained from deformation analyses (5,8):

$$t_b \propto \frac{R_o}{u}\sqrt{\frac{\rho_l}{\rho}}$$

Thus, whichever model is used, about the same qualitative dependence of breakup time on size, velocity, and density is obtained.

APPLICATION TO COMBUSTION INSTABILITY

Penner (9) has proposed that in order to maintain combustion stability in scaling from one rocket engine size to another, the ratio of chemical conversion time to wave time should be held constant, that is,

$$X \equiv t_i/t_w = \text{constant}$$

If we assume that the atomized liquid produced by the shock wave is rapidly burned as compared with the rate at which it is produced, then we may equate t_i with t_b. For the transverse acoustic mode, $t_w \propto r$, where r is the combustion radius. Applying equation (6) for a given liquid

$$X \propto \frac{R_o^{1.12}}{ru^{1.05}\rho^{0.48}} = \text{constant}$$

For a given magnitude of perturbation, u, the jet size should be scaled approximately in proportion to the combustor radius and the square root of the pressure. The above expression also indicates that if an engine is scaled to a larger size while retaining constant values of R_o and ρ, the perturbation velocity must be decreased in order to retain similarity with respect to combustion stability. This observation may have some bearing on the interpretation of model motor data for artificial disturbances.

Crocco (10) by an entirely different approach has derived the parameter τ_s/t_w which must lie outside certain limits in order to achieve stability. Obviously, if we make the same assumption about the relation between $\overline{\tau}_s$ and and t_b as we did with respect to t_i, the conclusions will be the same as were derived from the chemical conversion parameter.

A nonlinear solution for the transverse acoustic mode of oscillation has been obtained by Priem (11). For a vaporization limited model two parameters should be held constant in scaling to retain stability: the Mach number of the gas phase relative to the liquid phase and a heating rate number

$$\mathfrak{L} \equiv \frac{rm}{A}$$

If we assume that the value of m is determined by the atomization rate, that is, atomized drops vaporize quickly compared with the rate at which they are produced, then the rate may be written

$$m \propto \frac{1}{t_b V_j}$$

and

$$\mathfrak{L} \equiv \frac{rm}{A} \propto \frac{r}{t_b V_j A}$$

For a given liquid, substitution of equation (6) yields

$$\mathfrak{L} \propto \frac{ru^{1.05}\rho^{0.48}}{R_o^{1.12} V_j A} = \text{constant}$$

No clear cut scaling procedure is indicated here. If u and A can be maintained constant, then an increase in combustor radius or pressure or both must be compensated for by a corresponding increase in jet size and velocity. It should be pointed out that there is a lower limit below which no breakup occurs (12). Therefore, the previous discussion is not valid for sufficiently low perturbation velocities or relative gas velocities.

SUMMARY

Breakup times in a transverse gas flow have been measured in a shock tube for three sizes of jets of water, heptane, liquid oxygen, and three glycerol-water mixtures. In all cases the breakup time was found to decrease monotonically with an increase in gas velocity.

A model based on mass removal from a liquid boundary layer gives fair agreement with the observed values of breakup time. The model tends to give high values in the range of long breakup times ($t_b > 3$ msec) and tends to give low values for shorter breakup times ($t_b < 1$ msec), especially for the more viscous liquids.

With the assumption that liquid breakup is the rate controlling process, it is shown how similarity parameters for three different combustion instability theories could be evaluated.

The three theories are consistent in showing that, when all other factors are held constant, jet radius should be scaled in proportion to the combustor radius and the square root of the combustion pressure in order to maintain similarity with respect to stability. Furthermore, they are consistent in showing that scale-up without change in injector radius or jet velocity will reduce stability since a smaller value of perturbation velocity is required to maintain similarity.

SYMBOLS

A	engine contraction ratio
L	length of liquid sheet
$\mathcal{L}$	heating parameter
M	mass per unit length of jet
m	fraction burned per unit length
R_o	initial jet radius
r	combustor radius
Re_o	Reynolds number based on R_o, $R_o u \rho/\mu$
t	time
t_b	breakup time
t_i	chemical conversion time
t_w	wave time
u	gas velocity behind shock wave
$u_{l,av}$	arithmetic average velocity in liquid boundary layer

V	volume per unit length of jet
V_j	jet velocity
We_o	Weber number based on R_o, $We_o = \frac{\rho u^2 R_o}{\sigma}$
x	distance along liquid sheet from stagnation point
δ_l	liquid boundary layer thickness
μ	gas viscosity
μ_l	liquid viscosity
ν	kinematic viscosity, μ/ρ
ν_l	liquid kinematic viscosity, μ_l/ρ_l
ρ	gas density behind shock wave
ρ_l	liquid density
σ	interfacial tension
$\overline{\tau}_s$	average pressure sensitive time lag
χ	ratio of chemical conversion time to wave time

REFERENCES

1. Priem, R. J., and Morrell, G., Progress in Astronautics and Rocketry. Vol. 6 - Detonation and Two-Phase Flow. Academic Press, 1962, p. 305.

2. Lane, W. R., Industrial and Engineering Chemistry, 43, 1312 (1951).

3. Engel, O. G., Journal of Research, National Bureau of Standards, 60, 245 (1958).

4. Muirhead, J. C., Suffield Technical Paper No. 175, Defense Research Board, Canada, December, 1959.

5. Morrell, G., Eighth Symposium (International) on Combustion, Williams & Wilkins, 1962, p. 1059.

6. Morrell, G., NASA Technical Note D-1728, 1963.

7. Ames Research Staff, NACA Report 1135, 1953.

8. Gordon, G. D., Journal of Applied Physics, 30, 1759 (1959).

9. Penner, S. S., Jet Propulsion, 27, pt. 1, 156 (1957).

10. Crocco, L., and Cheng, Sin-I., Agardograph Number 9, Butterworths Scientific Pub., 1956.

11. Priem, R. J., and Guentert, D. C., NASA Technical Note D-1409, 1962.

12. Morrell, G., NASA Technical Note D-677, 1961.

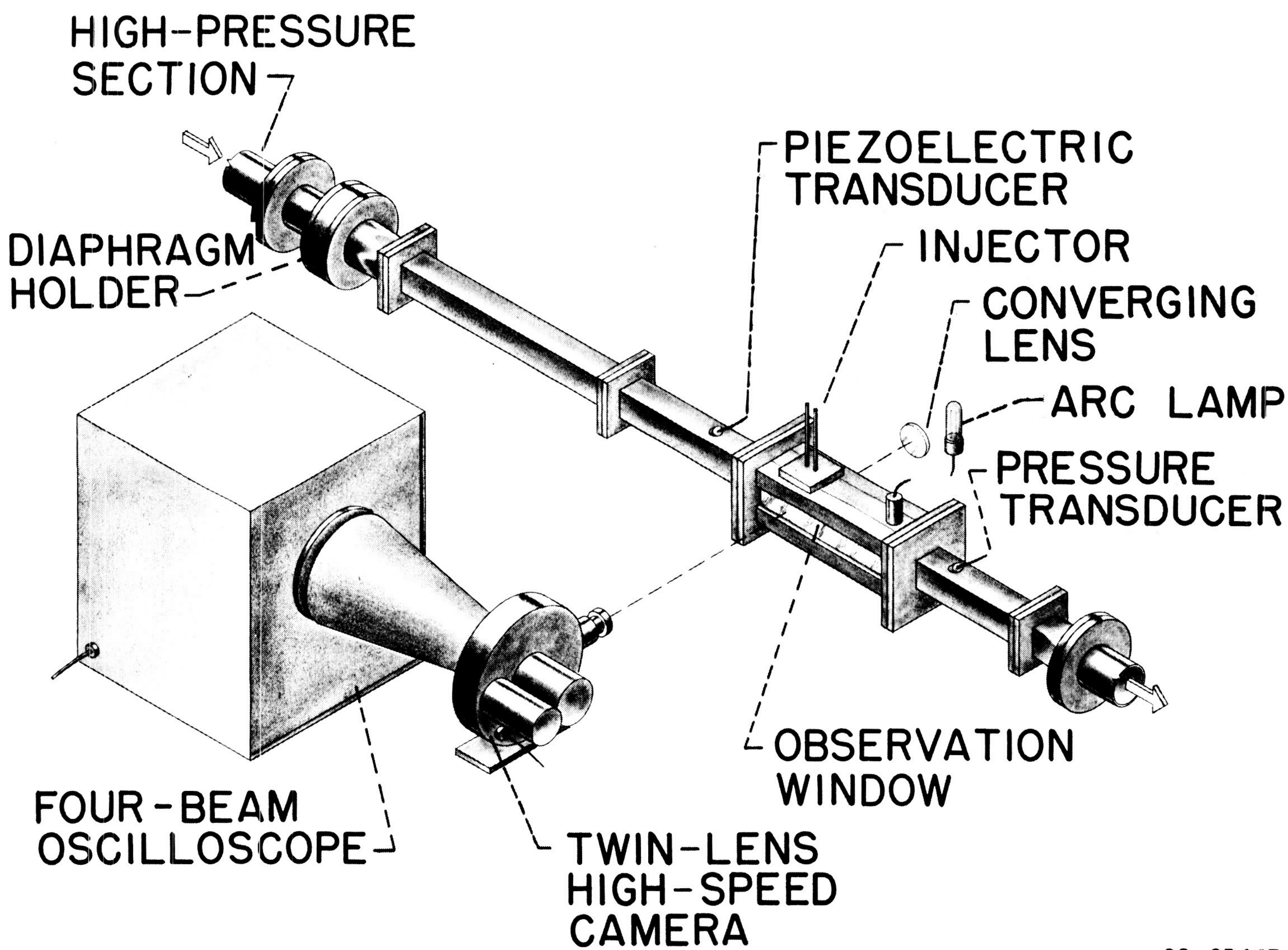
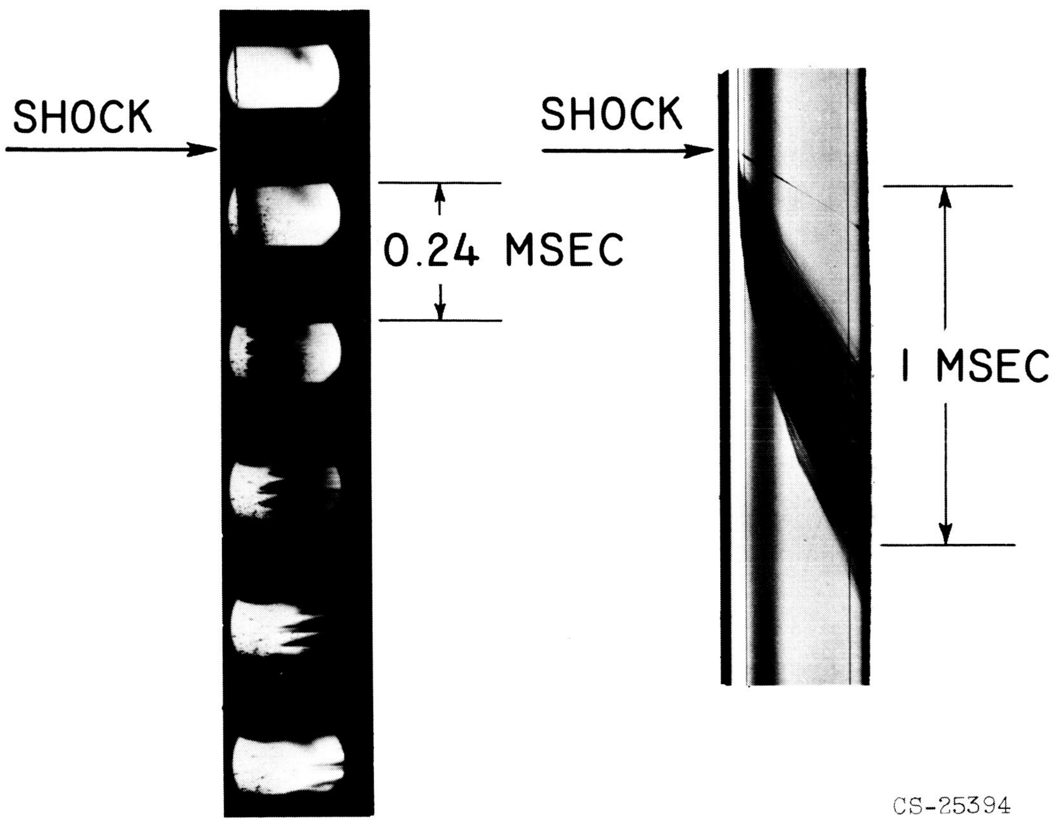


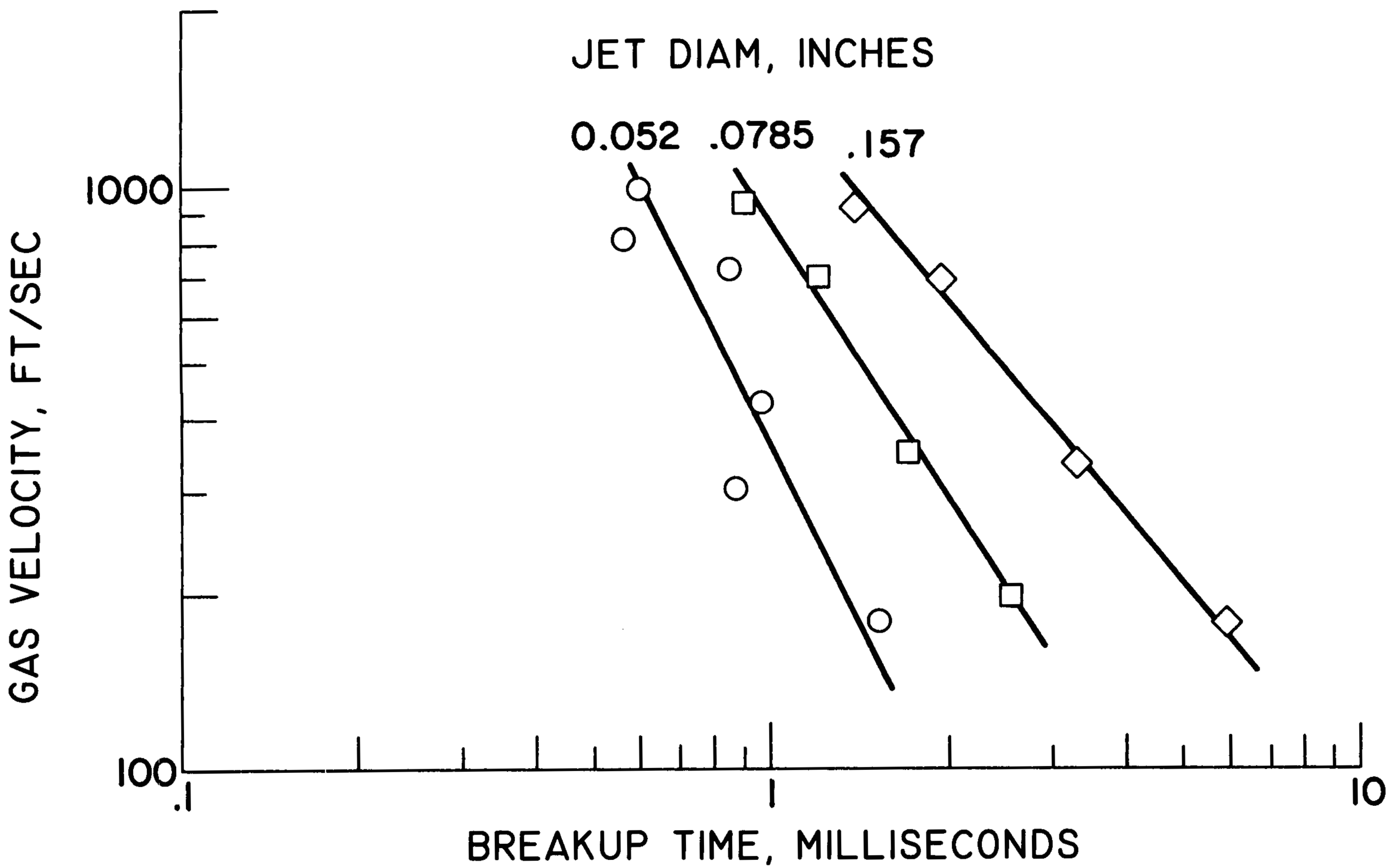
FIGURE 1. - SCHEMATIC DIAGRAM OF EXPERIMENTAL ARRANGEMENT.

E-2312



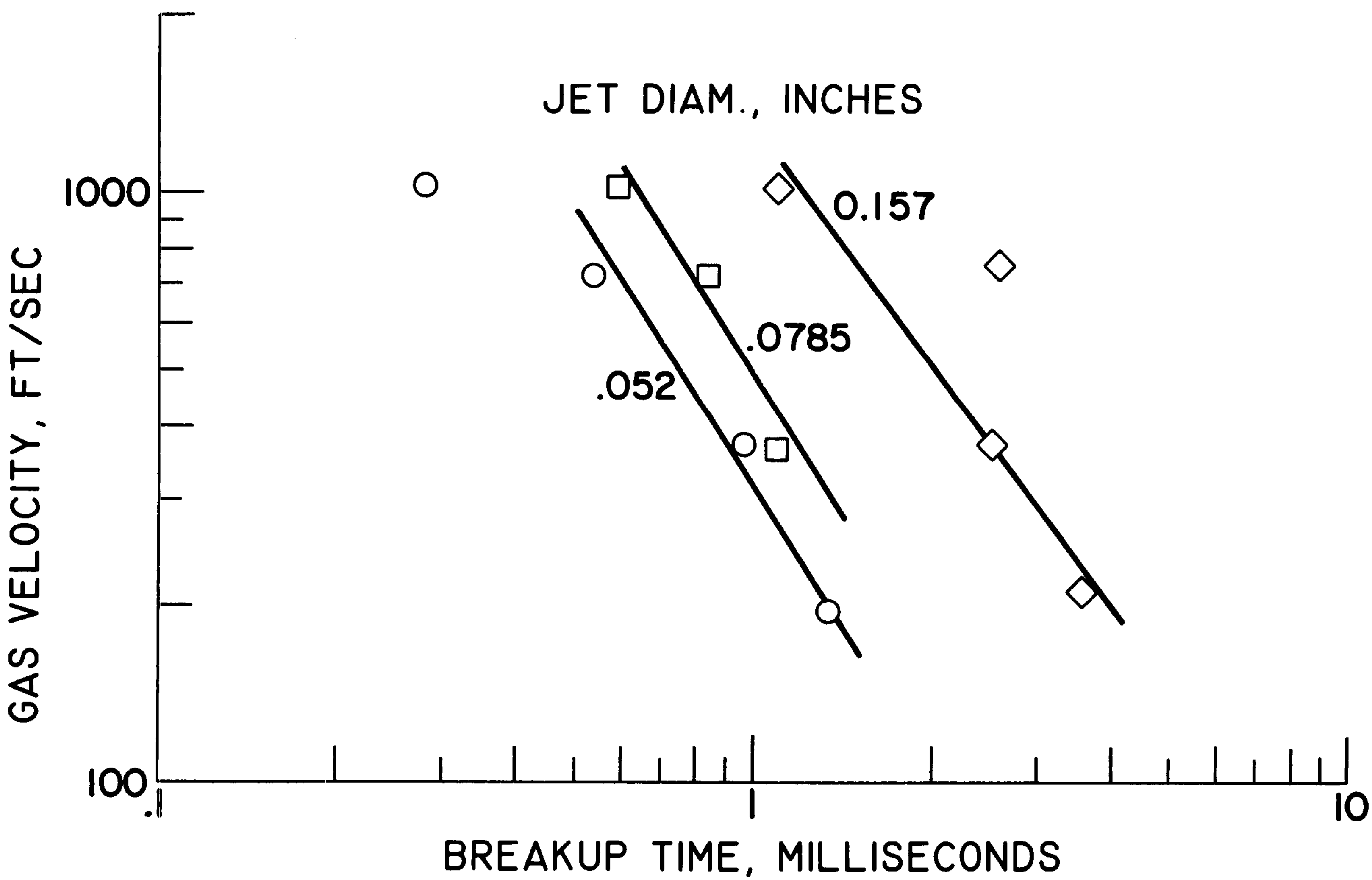
CS-25394

FIGURE 2. - EXAMPLES OF PHOTOGRAPHIC DATA OF JET BREAKUP. SHOCK VELOCITY, 1655±5 FEET PER SECOND; GAS VELOCITY, 732±5 FEET PER SECOND; JET DIAMETER, 0.052 INCH; BREAKUP TIME, 1.1 MILLISECONDS.



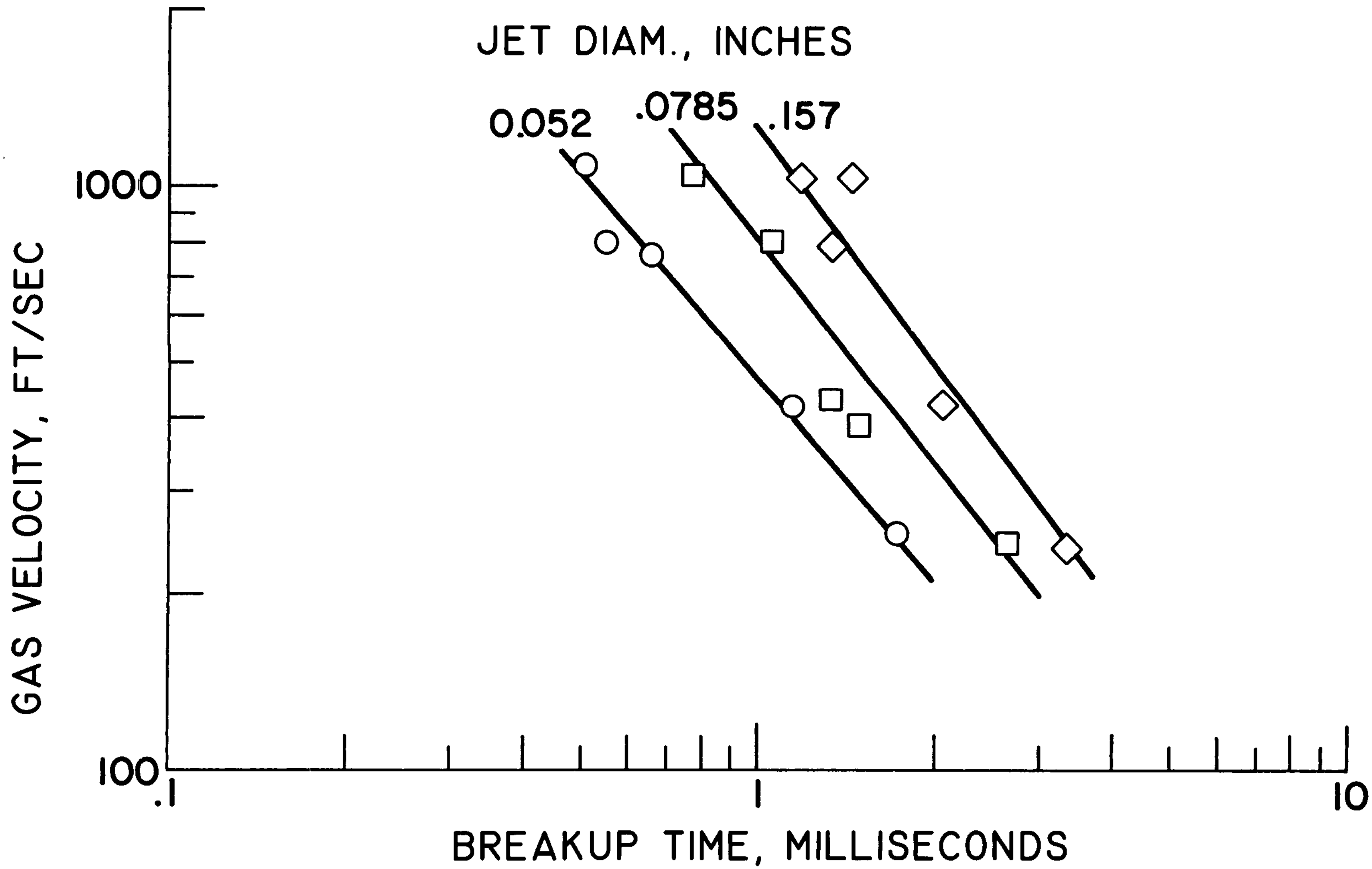
(a) DATA FOR WATER JETS.

FIGURE 3. - TYPICAL DEPENDENCE OF BREAKUP TIME ON GAS VELOCITY.



(b) DATA FOR HEPTANE JETS.

FIGURE 3. - CONTINUED. TYPICAL DEPENDENCE OF BREAKUP TIME ON GAS VELOCITY.



(c) DATA FOR 79% GLYCEROL.

FIGURE 3. - CONCLUDED. TYPICAL DEPENDENCE OF BREAKUP TIME ON GAS VELOCITY.

E-2312

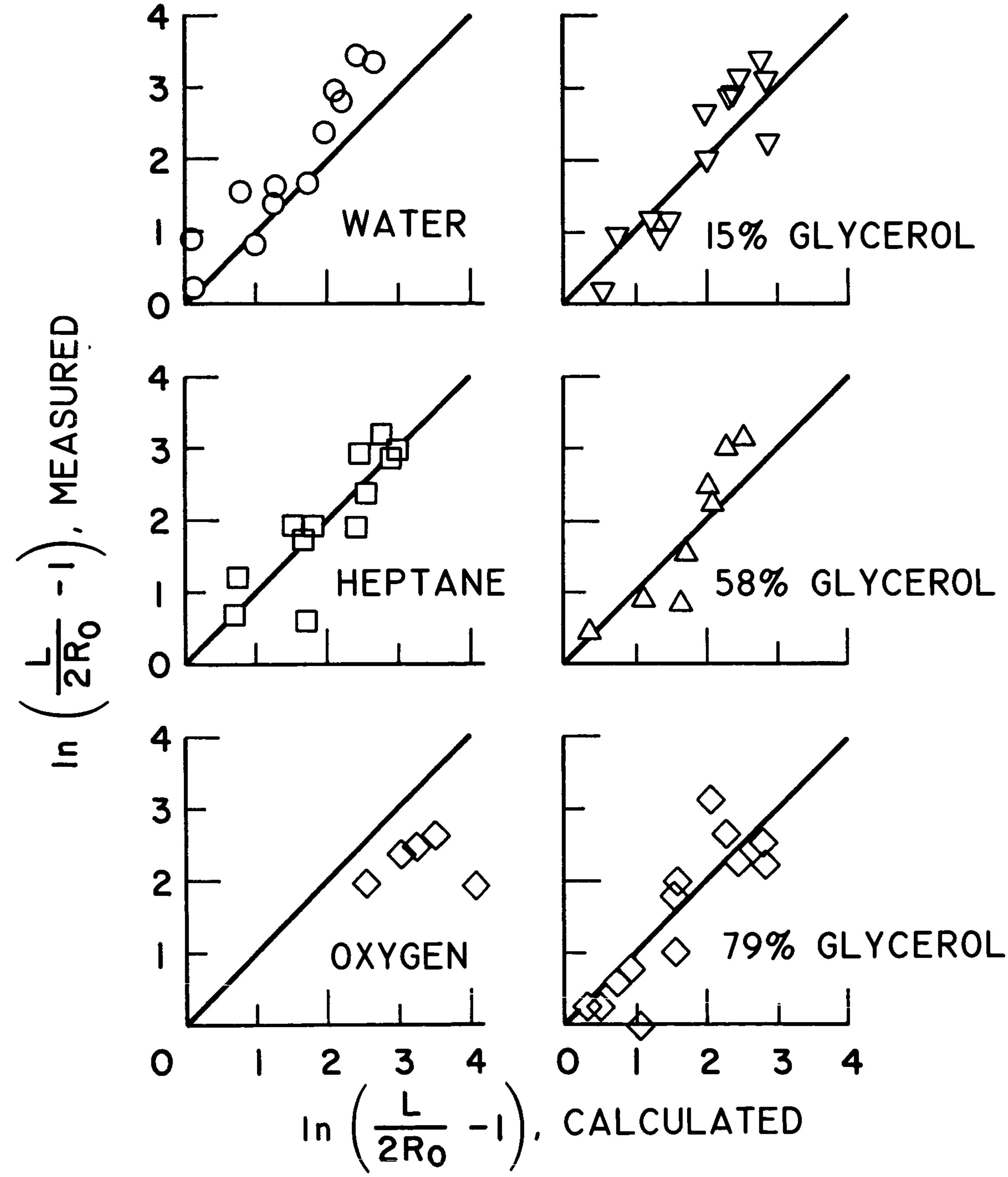


FIGURE 4. - COMPARISON OF MEASURED AND CALCULATED VALUES OF $(L/2R_o-1)$ BASED ON EQUATION (3).

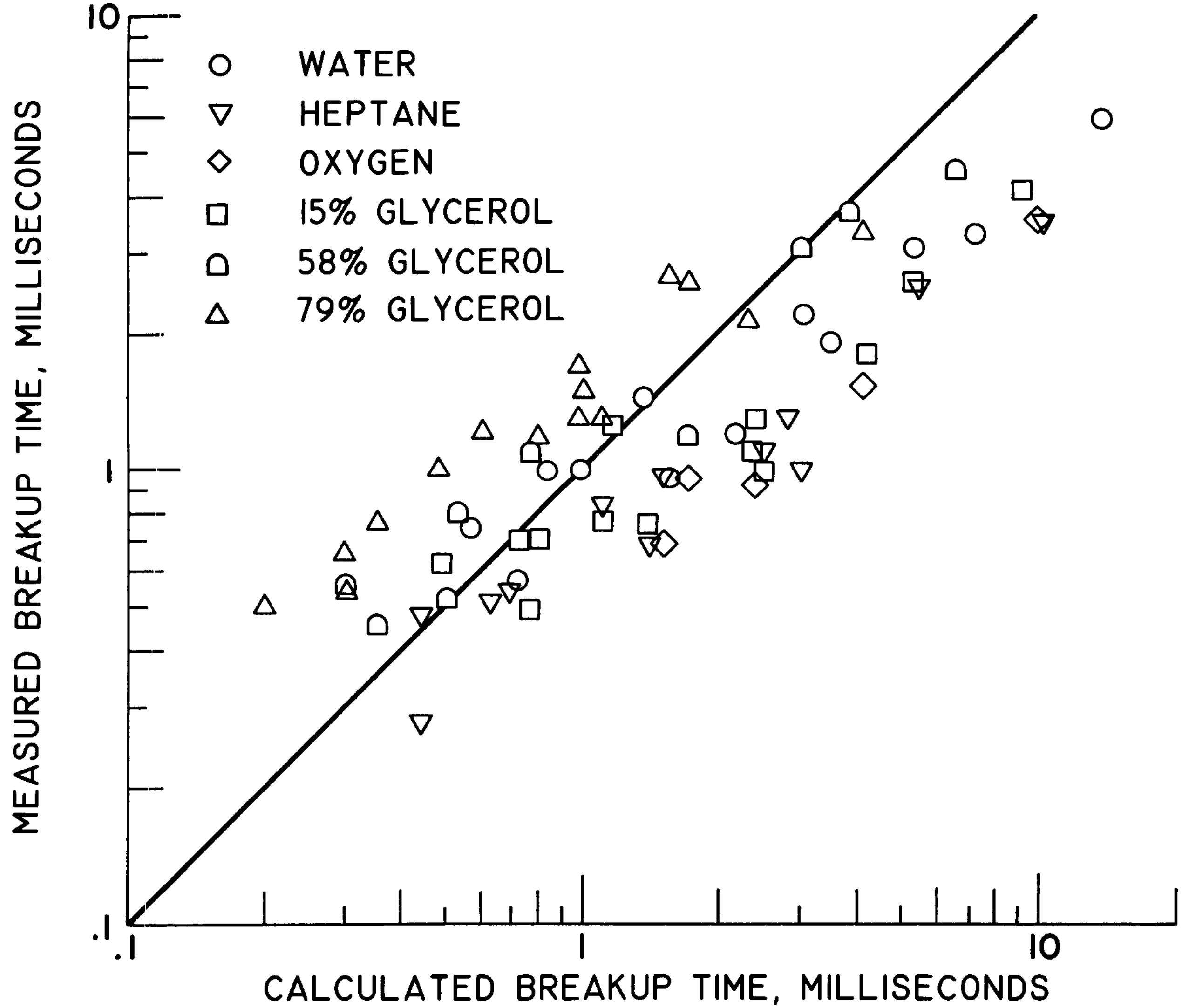


FIGURE 5. - COMPARISON OF MEASURED BREAKUP TIMES WITH VALUES CALCULATED FROM EQUATION 5.